Effect of the interlayer coupling on the Ni spin reorientation in Ni/Fe/Co/Cu(100)

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Ni/Fe/Co/Cu(100) films were epitaxially grown and investigated by photoemission electron microscopy. The magnetic correlation of the Ni and Co films was investigated by element-specific domain images. We found that the Ni magnetization exhibits a continuous rotation in the spin reorientation transition (SRT) region and that the Ni SRT thickness oscillates with the Fe film thickness.

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New structural phases of materials could be synthesized in the laboratory that open new opportunities for materials research. Two examples are the face-centered-cubic (fcc) Fe film on Cu(100) (Refs. 1 and 2) and the tetragonal distorted Ni film on Cu(100) (Ref. 3). For the Fe/Cu(100) system, the fcc Fe could be either ferromagnetic or antiferromagnetic.[4,5] The rich magnetic phases have stimulated great interest in studying the fcc Fe film.[6–10] In particular, structural characterizations reveal a direct connection between the magnetic phases and surface reconstruction, interlayer spacing, and local atomic distortions.[11,12] For the Ni/Cu(100) system, the most "surprising" phenomenon is the abnormal spin reorientation transition (SRT) of which the Ni magnetization switches from in-plane to out-of-plane directions as the Ni thickness increases.[13] Structurally, thin Ni film grows epitaxially on Cu(100) with its in-plane lattice extended to that of Cu and its out-of-plane lattice contracted.[3] This tetragonal distorted fcc structure generates a strain-induced perpendicular magnetic anisotropy that accounts for the unusual SRT mentioned above. Many research activities have been generated to understand the Ni SRT with respect to the magnetic anisotropy,[14,15] the magnetic domain structures,[16] the external magnetic field,[17] the effect of the capping layers,[18,19] etc. The rich magnetic properties of the Fe/Cu(100) and Ni/Cu(100) systems make it tempting to combine the Fe and Ni films on Cu(100) substrate to create new magnetic properties. Such an investigation has been developed in the last few years first in the study of the fcc Fe film on Ni (Refs. 7 and 9) and then extended to the magnetically coupled sandwiches.[20] The feasibility of such experiments has been greatly advanced by the development of x-ray magnetic circular dichroism (XMCD) which provides element-specific magnetic information.[21,22] In this paper, we report the results of our study of the SRT of Ni film in a magnetically coupled Ni/Fe/Co/Cu(100) system using photoemission electron microscopy (PEEM).

A Cu(100) single-crystal substrate was cleaned in an ultrahigh-vacuum chamber by cycles of Ar^+ sputtering at 2–3 keV and annealing at ~600 °C (Ref. 23). Ni, Fe, and Co films were grown epitaxially onto the Cu(100) substrate at room temperature and characterized by low-energy electron diffraction (LEED), reflection high-energy electron diffraction (RHEED), and Auger electron spectroscopy (AES). An eight-monolayer (8-ML) fcc Co film was first grown on the Cu(100). Fe and Ni films were then grown into crossed wedges to vary their thicknesses independently. The double wedges cover an area of 2 mm×2 mm with slopes of 15 ML/mm for Ni and 6 ML/mm for Fe. The sample was measured in the PEEM chamber at beamline 7.3.1.1. of the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory. The magnetic domain images were constructed by taking the intensity ratio of the images acquired at the L_3 and L_2 edges. All domain images shown in this paper have the size of 40 μm×40 μm.

We first studied the Ni/Fe(6 ML)/Cu(100) system at room temperature to identify the existence of the SRT of the Ni film using the *in situ* surface magneto-optic Kerr effect (SMOKE) technique. The Fe film at 6 ML is in the antiferromagnetic phase.[5] The perpendicular component of the magnetization ($M_\perp$) is obtained from the polar remnant Kerr ellipticity normalized by the Ni film thickness. Figure 1 shows $M_\perp$ as a function of Ni film thickness (d_{Ni}). $M_\perp$ is about zero in the thinner region, increases above a critical thickness, and saturates at thicker thickness. This behavior of $M_\perp$ represents the SRT of the Ni magnetization from the in-plane to out-of-plane directions. After the SMOKE measurement, we performed a PEEM study of Ni/Fe/Co/Cu(100) at the ALS. The existence of the oscillatory interlayer cou-

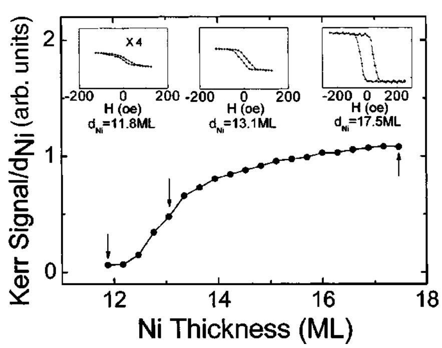

FIG. 1. Ni remnant perpendicular magnetization ($M_\perp$) vs Ni film thickness (d_{Ni}) in Ni/Fe(6 ML)/Cu(100). $M_\perp$ was obtained from the polar SMOKE signal divided by the Ni film thickness. The inset shows typical hysteresis loops at different Ni film thicknesses noted.

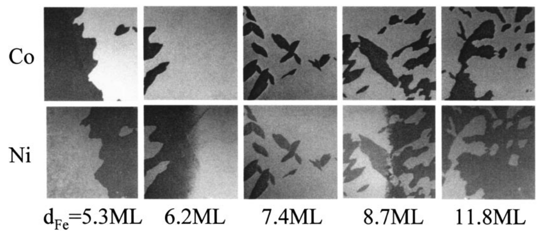

FIG. 2. Ni and Co magnetic domains of Cu(11 ML)/Ni(8.8 ML)/Fe/Co(8 ML)/Cu(100). The domain color change between the Ni and Co domains shows the existence of the oscillatory interlayer coupling across the fcc Fe film.

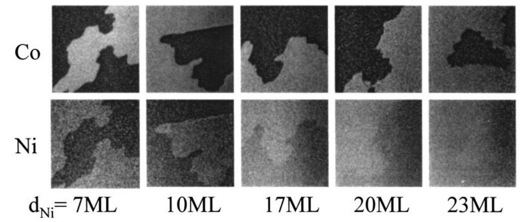

FIG. 4. Ni and Co domains as a function of Ni film thickness from Cu(11 ML)/Ni/Fe(5.3 ML)/Co(8 ML)/Cu(100). A magnetic field was applied prior to the measurement to line up the perpendicular component of the Ni magnetization.

pling across the fcc Fe was confirmed by analyzing the Ni and Co magnetic domain images from Ni(8.8 ML)/Fe/Co(8 ML)/Cu(100) in which the 8.8 ML Ni has an in-plane magnetization (Fig. 2). The Ni and Co magnetic domains have exactly the same shape, but their corresponding domain colors (white or dark) alternate with the Fe film thickness. Since different domain colors correspond to different magnetization directions, the alternating domain colors between the Ni and Co magnetic domains clearly prove the existence of an oscillatory interlayer coupling between the Ni and Co films across the fcc Fe film.

The SRT of Ni was then studied by PEEM in Ni/Fe(6.5 ML)/Co(8 ML)/Cu(100) as a function of the Ni film thickness. The 6.5 ML Fe produces a ferromagnetic coupling (FC) between the Ni and Co films. Figure 3(a) shows a series of the Ni and Co domain images in the Ni SRT region. At the thinner Ni thickness where the Ni magnetization is in the plane of the film, the Ni domain is identical to that of Co due to the FC. As the Ni magnetization switches to the out-of-plane direction with increasing thickness, the Ni domain gradually becomes different from that of Co. To better view the difference between the Ni and Co magnetic domains, we subtracted the Co image from the Ni image [last row of Fig. 3(a)]. The Ni domain character discussed above can be clearly seen in the subtracted image: the new feature in the Ni domain increases continuously as the Ni magnetization changes from the in-plane to out-of-plane directions. This is because as the Ni magnetization possesses the SRT, its perpendicular magnetization component can be either up or down to produce different domain colors even when its in-plane magnetic component remains in the same direction as that of Co. To have a quantitative idea of the Ni and Co domain relation in the SRT region, we calculated the magnetic correlation from the Ni and Co magnetic domain images in Fig. 3(a) using the following formula:

$$f=\frac{\Sigma_i(I_i^{\mathrm{Co}}-\langle I^{\mathrm{Co}}\rangle)(I_i^{\mathrm{Ni}}-\langle I^{\mathrm{Ni}}\rangle)}{\sqrt{\Sigma_i(I_i^{\mathrm{Co}}-\langle I^{\mathrm{Co}}\rangle)^2\Sigma_i(I_i^{\mathrm{Ni}}-\langle I^{\mathrm{Ni}}\rangle)^2}}. \tag{1}$$

Here I_i^{Ni} and I_i^{Co} are the intensities of Ni and Co domain images from the ith position pixel, and $\langle I^{\mathrm{Co}}\rangle$ and $\langle I^{\mathrm{Ni}}\rangle$ are the averaged intensities of the Co and Ni domain images. Figure 3(b) shows the correlation calculated from Eq. (1). Indeed, the correlation function shows a monotonic decrease from ~100% to ~0% as the Ni magnetization switches from the in-plane to out-of-plane directions. The continuous decrease of the magnetic correlation over a wide range of Ni thickness [Fig. 3(b)] indicates that the Ni magnetization is partially coupled to the Co magnetization in the SRT region. Since the Co magnetization is in the plane of the film due to the strong magnetic shape anisotropy, the coupling must come from the in-plane component of the Ni magnetization: i.e., the Ni magnetization should have a continuous rotation in its SRT. It was shown that the SRT of Ni film in Ni/Cu(100) (Ref. 14) and Ni/Cu/Co/Cu(100) (Ref. 21) has a continuous rotation nature. However, the continuous rotation of the SRT depends on the higher-order magnetic anisotropy. Under certain conditions, the SRT could become a first-order transition[14] and even develop stripe domains such as in the Fe/Cu(100) system.[24] To prove the continuous rotation of the Ni SRT in the Ni/Fe/Co/Cu(100) system, we did the following experiment. An external magnetic field was applied to the film to saturate the Ni magnetization in the perpendicular direction prior to the PEEM measurement so that the perpendicular component of the Ni magnetization in the SRT region stays in the same direction. Thus the Ni magnetic domains after applying the magnetic field should reflect the directional change of the Ni in-plane magnetic component. Figure 4 shows the Co and Ni PEEM images of the Ni/Fe(5.3 ML)/Co(8 ML)/Cu(100) after applying the external magnetic field. Since the Ni domains must come from the in-plane component of the Ni magnetization, the identical shapes of the Ni and Co domains show that the Ni in-plane component follows that of Co [the opposite color of the Ni and Co

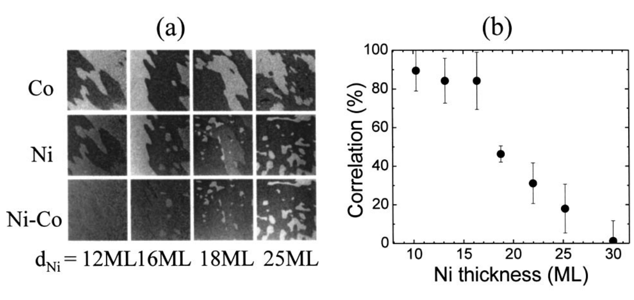

FIG. 3. (a) Ni and Co domains as a function of Ni film thickness from Cu(11 ML)/Ni/Fe(6.5 ML)/Co(8 ML)/Cu(100). The last row was constructed by subtracting the Co domains from the Ni domains. (b) Correlation function calculated from the Ni and Co magnetic domains.

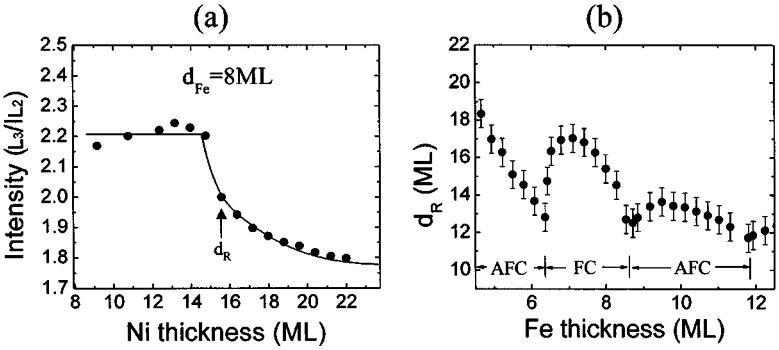

FIG. 5. (a) Ni L_3/L_2 intensity of Cu(11 ML)/Ni/Fe(8 ML)/Co(8 ML)/Cu(100) vs the Ni thickness. The decrease of the XMCD shows the in-plane to out-of-plane SRT of the Ni film. (b) Ni SRT thickness (d_R) vs the Fe film thickness. The solid lines are a guide to the eye.

domains is due to the antiferromagnetic interlayer coupling (AFC) between the Ni and Co films]. Figure 4 also shows that the Ni domain contrast decreases continuously as the Ni thickness increases to change its magnetization from in-plane to out-of-plan directions. This continuous decrease of the Ni domain contrast indicates the continuous decrease of the Ni in-plane magnetization during the SRT, thus proving the continuous rotation of the Ni magnetization. This phenomenon occurs also for the ferromagnetically coupled Ni/Fe/Co/Cu(100). Figure 5(a) shows the Ni XMCD signal, constructed from the L_3/L_2 ratio, of Ni/Fe(8 ML)/Co(8 ML)/Cu(100) after applying the external magnetic field. The 8 ML Fe produces a FC between the Ni and Co films. The XMCD signal is about a constant as the Ni magnetization is in the plane of the film, decreases continuously in the SRT region, and then saturates as the Ni magnetization changes to the perpendicular direction of the film plane. This result clearly shows the continuous rotation of the Ni magnetization in the SRT region. Defining the Ni SRT thickness (d_R) as where the XMCD signal starts to drop [shown in Fig. 5(a)], we measured d_R as a function of the Fe film thickness [Fig. 5(b)]. The d_R clearly oscillates with the Fe film thickness with the minimum at the FC/AFC coupling boundaries. This result shows that the interlayer coupling, regardless of the FC or AFC, enhances the Ni SRT thickness. The d_R enhancement is expected because the interlayer coupling between the Ni and Co films favors the in-plane Ni magnetization so that the Ni film has to reach a thicker thickness to build up enough perpendicular magnetic anisotropy to realize the SRT.

In summary, we investigate the SRT of the Ni film in magnetically coupled Ni/Fe/Co(8 ML)/Cu(100) using the PEEM technique. By analyzing element-specific domain images, we found that the Ni magnetization exhibits a continuous rotation in the SRT region. The in-plane magnetic component of the Ni film couples to the Co magnetization by the interlayer coupling. The oscillatory interlayer coupling results in an oscillatory Ni SRT thickness (d_R) with the d_R enhanced in both the FC and AFC regions.

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